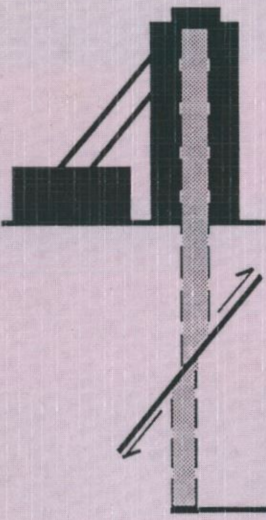
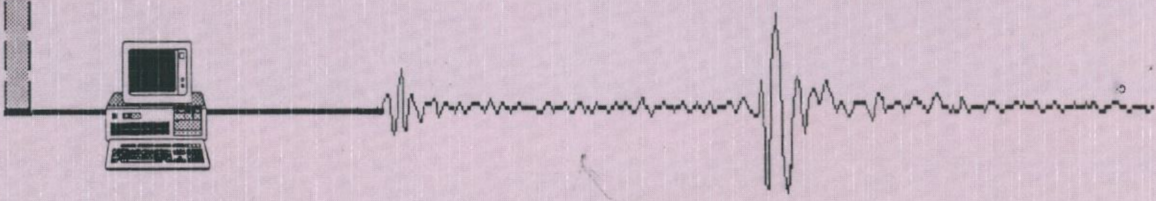
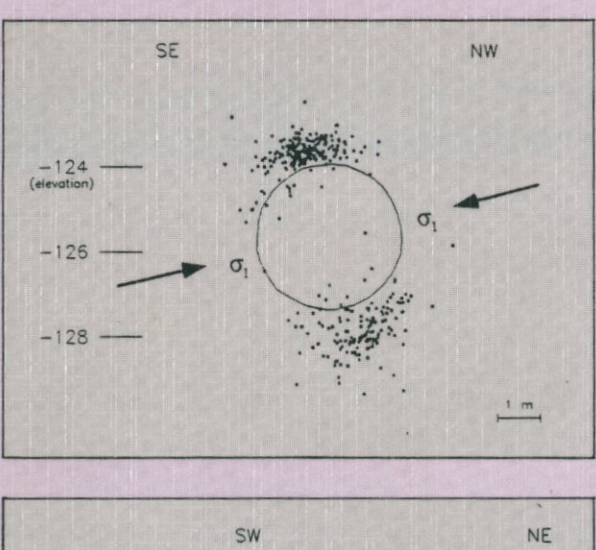
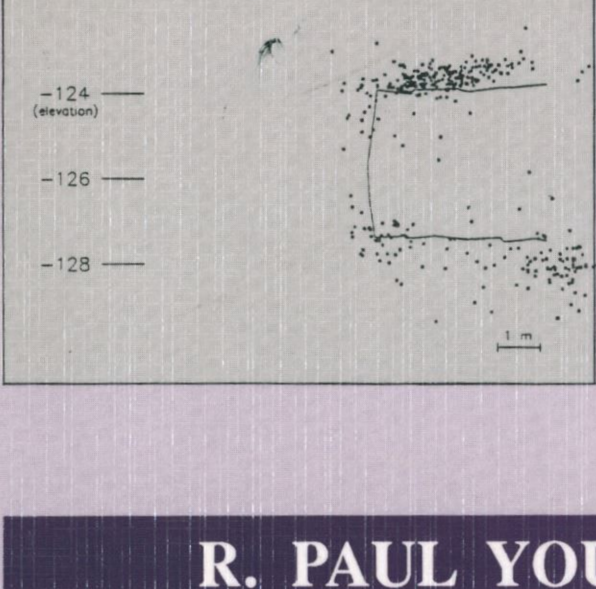
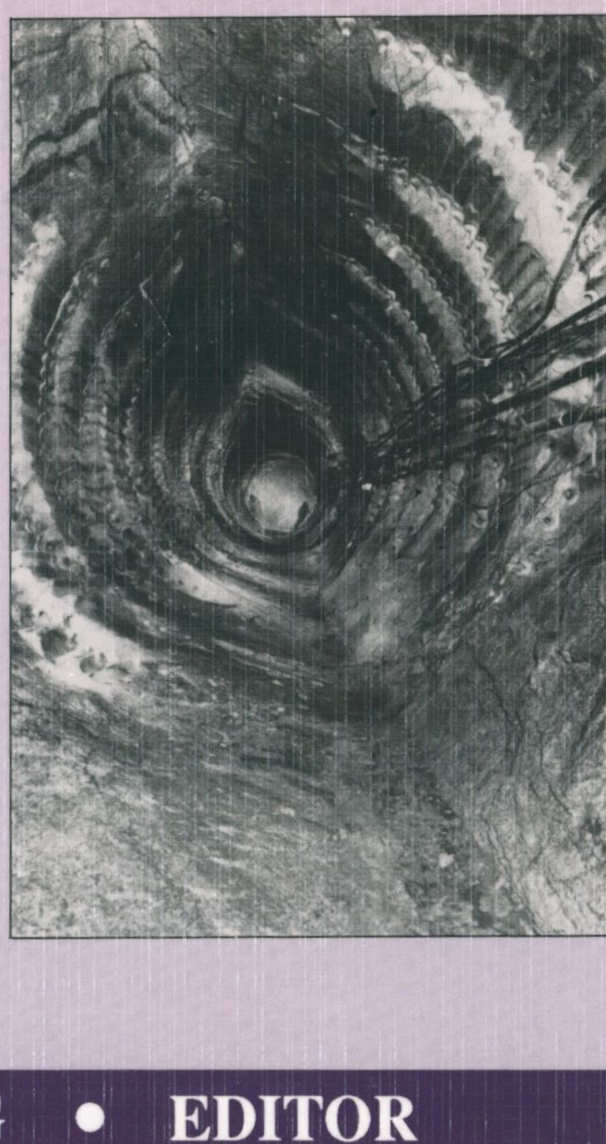


ROCKBURSTS AND SEISMICITY IN MINES









R. PAUL YOUNG • EDITOR

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Tectonic stresses in mine seismicity: Are they significant?

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ABSTRACT: Lithostatic stresses and their redistribution around mine excavations are thought to be the dominant driving force in the generation of most mine tremors and rockbursts. In some cases, however, it has been suggested that tectonic stresses also play a significant role. These cases have often involved the largest mine tremors, M 4 to 5+. I have reviewed the available focal mechanisms from cases of mining-induced seismicity in an attempt to evaluate the effects of tectonic stresses. Data from the World Stress Map Project were used as a basis for characterizing the broad-scale tectonic stresses operative in the mining districts which were investigated. Based on the focal mechanism data, compressive tectonic stresses appear to play a major role in the generation of mine seismicity worldwide. In general, mine tremors and rockbursts occur in regions being subjected to moderate to high horizontal compressive tectonic stresses and which often possess moderate and sometimes high levels of natural seismicity. The larger events, for which focal mechanisms are most often available, are generally the result of reverse and sometimes strike-slip faulting. This mode of deformation probably reflects the increases in shear stress along pre-existing zones of weakness i.e., faults, due to unloading. In cases where tectonic stresses may not be the primary driving force, they could act to trigger mine tremors where the principal source of strain energy is due to the redistributed lithostatic stresses.

1 INTRODUCTION

Since the early investigations in the 1950's in the gold mines of South Africa, rockbursts and mine seismicity have been considered to be the mechanisms by which redistributed and concentrated lithostatic stresses around mine excavations are violently released. Other components of the in situ stress field, such as tectonic and residual stresses, have also been recognized by several investigators as having a possible effect on rockbursts and mine tremors (e.g., McGarr et al. 1975; Gibowicz 1984; Knoll and Kuhnt 1990; Wong 1993). In particular, cases influenced by tectonic stresses have often involved some of the largest mine tremors ever observed (magnitude [M] 4 to 5+), events occurring at distances beyond a few tens of meters or beneath the mine workings, or events resulting from seismic slip along large faults. In addition to the in situ stresses, the role of pre-existing faults has been critical in many cases of mine seismicity as described by numerous investigators (e.g., Gay et al. 1984).

To understand completely the role of tectonic stresses in mine seismicity, the other components of the in situ stress field must be characterized. Unfortunately, it has been difficult to distinguish and quantify these components in mines. Overcoring, which is by far the most common method for characterizing the in situ stresses in mines, appears to suffer from a number of problems and hence is not considered to be wholly reliable (Zoback 1992). The determination of mine tremor and rockburst focal mechanisms, which have been increasingly utilized in mine seismicity research, has proven to be an extremely useful tool. This is especially the case if the characteristics of the tectonic stress field are known based on other types of data such as earthquake focal mechanisms and other in situ measurements (e.g., borehole breakouts and hydraulic fractures).

In 1986, the World Stress Map Project of the International Lithosphere Program was initiated with the objective of compiling a global database of contemporary in situ stress measurements in the earth's crust using a variety of geophysical and geological techniques (Zoback 1992). This data has allowed for the first time, a comprehensive view of crustal stresses on a global scale. In this paper, I have reviewed, in the context of these tectonic stresses, much of the available published focal mechanism data from cases of mining-induced seismicity in an attempt to evaluate their role in the generation of mine tremors and rockbursts.

2 CRITERIA FOR SEISMIC SLIP

In general, most mine tremors and rockbursts are no different than tectonic earthquakes in their source processes; both are the result of shear failure in brittle rock (McGarr 1971; Spottiswoode and McGarr 1975). (See Wong and McGarr [1990] for a discussion of one form of non-shear failure in mine seismicity.) Brace and Byerlee (1966) suggested that the primary cause of earthquakes is frictional sliding (stick-slip motion) on pre-existing faults although the fracturing of intact rock on a small scale may also be involved. McKenzie (1969) stated that pre-existing faults may slip even at very low resolved shear stresses before the failure of intact rock and the formation of new fractures. Furthermore, Raleigh et al. (1972) suggested that seismic slip along pre-existing zones of weakness is favored over fracture of intact rock if the zone is oriented within 10° to 50° of the maximum principal stress (Figure 1). This observation was in reference to a case of induced seismicity due to fluid-injection at the Rangely oil field in Colorado.

Based on an analysis of heterogeneous fault strength in a pervasively fractured crust, Hill and Thatcher (1992) suggested that: (1) slip will be energetically favored on faults oriented 45° to 50° to the maximum principal stress if the coefficient of friction along these faults is only 20% to 25% lower than along faults at the optimum Coulomb angle of 25° to 30° with typical intrinsic coefficients of 0.70 to 0.75; (2) for very small values of frictional strength and low ambient shear stress, the 45° angle for optimal fault slip is only weakly favored over a variety of fault orientations centered on 45°; and (3) poorly oriented faults with angles greater than 80° can possibly slip if the effective coefficient of friction along such faults is less than 0.2.

Because shear failure can occur along faults or fractures even when they are oriented rather unfavorably to the maximum principal stress, advancing such pre-existing zones of weakness towards failure may not require large increases in shear stress. Observations of other forms of induced seismicity (e.g. reservoir induced) suggest that low levels of induced stresses can trigger seismic slip on faults and other pre-existing zones of weakness if they are already stressed to a state of near failure.

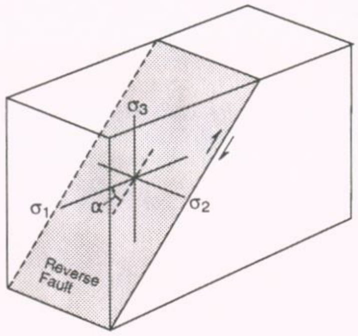

Figure 1. Illustrated is a block diagram of a reverse fault in a compressional stress regime where the maximum (σ_1) and intermediate (σ_2) principal stresses are horizontal. The minimum principal stress (σ_3) due to the lithostatic load is vertical. Seismic slip will occur on a pre-existing zone of weakness e.g., fault rather than the fracture of intact rock if it is oriented favorably to σ_1. This orientation, as indicated by the angle α, is generally 10° to 50° although the angle is dependent upon the effective coefficient of friction along the fault plane. The maximum shear stress acting on the fault plane is equal to $1/2(\sigma_1 - \sigma_3)$ acting in a direction which bisects the angle between σ_1 and σ_3.

A specific example of a small triggering stress was associated with the seismicity induced by surface mining in a Wappinger Falls, New York quarry. A sequence of earthquakes with a mainshock of body-wave magnitude (m_b) 3.3 occurred at depths of less than 1.5 km beneath an active limestone quarry (Pomeroy et al. 1976). The mainshock focal mechanism indicated thrust faulting and a northeast-southwest trending P-axis. Pomeroy et al. (1976) suggested that crustal unloading due to the quarry operations in the highly compressive stress regime in this part of the eastern U.S. triggered the earthquake activity. The triggering or unloading stress was estimated to be only 7 bars.

3 MINE SEISMICITY AND TECTONIC STRESSES

With these criteria and examples in mind, let us examine some of the most significant cases of mine seismicity worldwide to assess whether tectonic stresses are a factor in their generation. In the following, selected references are cited which I believe are notable and representative of the available published focal mechanism data.

3.1 *United States*

Within the U.S., the best documented cases of mine seismicity occur in the silver, lead, and zinc mining district of the Coeur d'Alene in northern Idaho and the coal mining areas of the eastern Wasatch Plateau and Book Cliffs in central Utah (Figure 2). Both cases occur within the western U.S., where several tectonic stress regimes exist (Zoback and Zoback 1989), in large part because of the proximity to a major plate boundary along the Pacific Coast and the high level of associated tectonism.

Focal mechanisms determined by Lourence et al. (1993) for 106 tremors in the Lucky Friday mine in the Coeur d'Alene district exhibit predominantly strike-slip and oblique-reverse faulting with generally north-south oriented P-axes (Figure 2). The strike-slip faulting focal mechanism of a M 4.1 earthquake which occurred at a depth of about 10 km, 15 km northeast of the Lucky Friday mine indicates a northwest-southeast trending P-axis (Sprenke et al. 1991). These mechanisms are all consistent with the Coeur d'Alene district being located within the Pacific Northwest compressional stress province as defined by Zoback and Zoback (1989) (Figure 2) rather than an extensional regime as suggested by Sprenke et al. (1991). Overcoring measurements in the vicinity of the Lucky Friday mine also indicate a compressional stress field with the northwest-southeast trending maximum principal stress about 1.3 times greater than the lithostatic or minimum principal stress (Lourence et al. 1993).

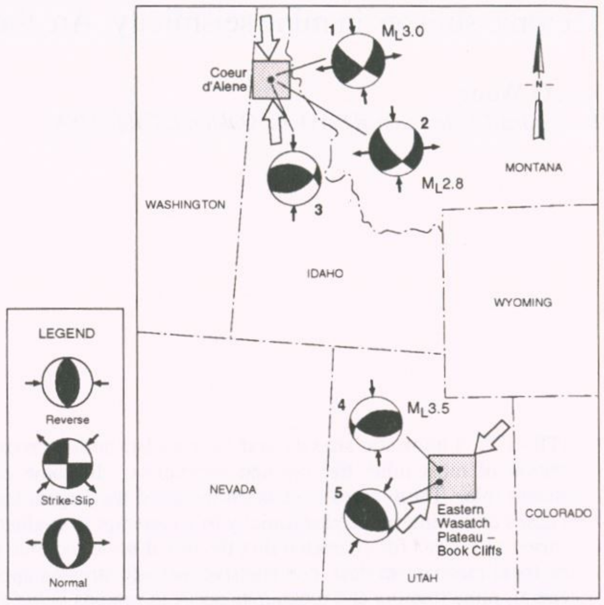

Figure 2. Typical focal mechanisms of mine seismicity in the intermountain U.S. Inward arrows on focal mechanisms indicate horizontal projections of the maximum principal stress and outward arrows represent the minimum principal stress. Mechanisms 1 – 3 are from Lourence et al. (1993) and 4 – 5 from Wong et al. (1989). Magnitudes of largest tremors are shown. Large arrows indicate the regional maximum principal stress direction.

The mine tremors in the Coeur d'Alene appear to be similar to tectonic earthquakes based on the focal mechanism data; both are the result of generally strike-slip or reverse faulting in a compressive stress regime. This suggests that these mine tremors can be viewed as triggered earthquakes and that tectonic stresses play a major role in their generation.

In the eastern Wasatch Plateau, focal mechanisms of mine tremors of up to Richter magnitude M_L 3.5, exhibit reverse faulting on generally west-to-northwest-trending planes (Wong et al. 1989) (Figure 2). These events occur as deep as 2 to 3 km beneath the mines which are located only a few hundred meters beneath the ground surface. Williams and Arabasz (1989) determined 10 focal mechanisms for mine tremors beneath the East Mountain mines in the eastern Wasatch Plateau; all but one mechanism exhibited reverse faulting in response to a northwest to northeast-oriented maximum principal stress. As is the case for the Coeur d'Alene, the eastern Wasatch Plateau is located adjacent to the Intermountain seismic belt, a major zone of seismicity in the western U.S. A composite focal mechanism of three small earthquakes, which occurred about 5 km away from the coal mines, indicates reverse faulting and a northeast-southwest P-axis (Wong et al. 1989). The latter is consistent with the suggestion that this area occurs within a stress field which is characterized by northeast-southwest compressive stresses. In contrast, the tectonic stress field of the Intermountain U.S. surrounding the eastern Wasatch Plateau and Book Cliffs is extensional in nature (Zoback and Zoback 1989).

Based on two-dimensional finite element modeling, Wong (1985) estimated that the stresses induced by coal mining could be as large as several hundred bars in the vicinity of the mine workings and still a few bars at depths of 2 km beneath the mines. These observations suggest that at least some of the mine seismicity in the eastern Wasatch Plateau, including the larger events, are probably due to triggering by unloading of tectonically pre-stressed faults in a compressive stress regime (Wong 1985; Wong et al. 1989).

Although no known focal mechanism data are available, some coal mining areas in the eastern U.S. have been subjected to mine tremors. One such area is Buchanan County in western Virginia (Bollinger 1989). The eastern U.S. is a region characterized by generally northeast-southwest oriented compressive tectonic stresses and a low to moderate level of earthquake activity (Zoback and Zoback 1989).

3.2 *Eastern Canada*

The deep metalliferous mines of eastern Canada, particularly in the Sudbury Basin of northern Ontario, have undergone significant mine seismicity and rockbursts in the past decade. This portion of eastern Canada is also seismically active with earthquakes resulting from reverse, and sometimes strike-slip faulting in a compressive tectonic stress field (Adams and Bell 1991). The maximum principal stress in eastern Canada is generally oriented northeast to east although there appears to be a wide range of local variability (Adams and Bell 1991) (Figure 3). These horizontal compressive stresses are very high, often being at least two times larger than the lithostatic stress.

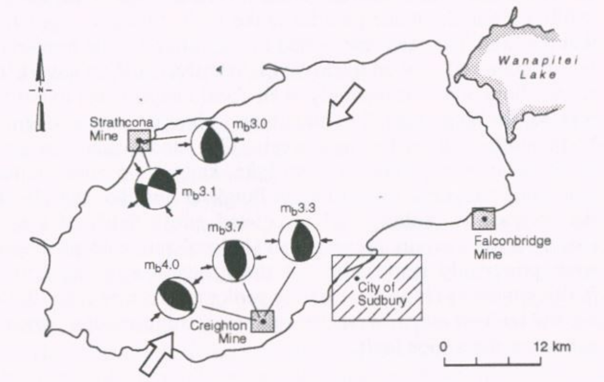

Figure 3. Typical focal mechanisms of mine seismicity in the Sudbury Basin. Focal mechanisms and base map (modified) are from Wetmiller et al. (1990).

Wetmiller et al. (1990) determined focal mechanisms for five large mine tremors in the Sudbury Basin between 1984 and 1987 (Figure 3). The mechanisms of two events in the Strathcona mine, m_b 3.1 and 3.0, exhibit strike-slip and reverse faulting with northwest-southeast and east-west-trending P-axes, respectively. The focal mechanisms of three Creighton mine tremors, m_b 4.0, 3.3, and 3.7, exhibit reverse faulting in response to a northeast-southwest to east-west-oriented compressive stress field. As noted by Wetmiller et al. (1990), four of these large mine tremors appear to be very similar to tectonic earthquakes in that they are the result of generally reverse faulting in the compressive tectonic stress field of eastern Canada (Figure 3).

Urbancic and Young (1993) also report reverse faulting in the Strathcona mine based on 796 microseismic ($M < 0$) focal mechanisms. Most of the mechanisms exhibit northeast-striking reverse faulting in response to a northwest-southeast oriented maximum principal stress similar to the m_b 3.1 mine tremor mechanism determined by Wetmiller et al. (1990). This stress orientation appears to correspond to the local stress field as indicated by overcoring tests. A smaller number of reverse faulting focal mechanisms indicate a northeast-southwest compressive stress field similar to the regional tectonic stress field (Urbancic and Young 1992) (Figure 3). These data suggest that both the local and regional tectonic stress fields influence the generation of seismicity in this mine. The local stress field may represent a distortion of the regional stress field due to the mine openings. It may also be the case that northwest-southeast compression actually represents a local variation of the regional stress field on the northwestern side of the Sudbury Basin where the Strathcona mine is located (Figure 3). Although the data of Urbancic and Young (1993) are for much smaller events than the other examples cited in this study, the observation that even such small tremors are the result of reverse and not normal faulting is noteworthy (see Section 4).

3.3 *Europe*

Mine seismicity is fairly widespread in Europe involving a wide range of mineral deposits. Some of the earliest studies were of mine tremors in Polish mines. Gibowicz (1984) computed focal mechanisms for four large mine tremors which occurred in three different mining districts in Poland. Two events were the result of normal faulting although their focal mechanisms exhibit different T-axes orientations: northwest compared to northeast (Figure 4). The tremors were a M_L 4.5 event on 24 June 1977 located between two copper mines in the Lubin Basin and a M_L 4.3 event on 30 September 1980 in the Szombierki coal mine near Bytom in the Upper Silesian Basin.

A M_L 4.6 event in the Belchatow surface coal mine, which occurred on 29 November 1980, resulted from reverse or possibly strike-slip faulting in response to generally northeast-southwest compressive stresses (Figure 4). The focal mechanism of a second large Szombierki mine tremor, M_L 4.1, on 12 July 1981, exhibits oblique-reverse slip and also a northeast-southwest P-axis similar to the Belchatow event.

According to Grünthal and Stromeyer (1992), the tectonic stress field in eastern Europe is characterized by northeast-southwest compressive stresses (Figure 4). Thus the two reverse faulting focal mechanisms (No. 1 and 4; Figure 4) suggest that the Belchatow and 1981 Szombierki tremors were directly influenced by the tectonic stress field. In contrast, the normal faulting mechanisms suggest that for events No. 2 and 3 (Figure 4), the lithostatic stresses were the most important (Gibowicz 1984). In all cases, however, because underground mining is performed at depths of less than 1 km, Gibowicz (1984) suggested that tectonic stresses must be involved to some degree in the generation of these large mine tremors since the lithostatic stresses are relatively small. All four mine tremors had focal depths of 2 km or less and thus the interaction between lithostatic and tectonic stresses may be complex with either being dominant; specifically, the principal stresses may be nearly equivalent such that the orientations of the maximum and minimum principal stresses are interchangeable.

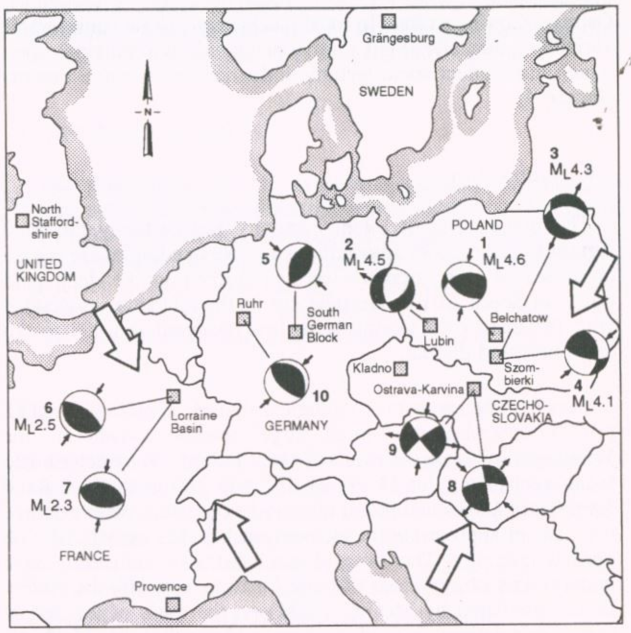

Figure 4. Significant occurrences of mine seismicity in Europe and typical focal mechanisms of mine tremors. Focal mechanisms are: 1–4, Gibowicz (1984); 5, Knoll and Kuhnt (1990); 6 – 7, Hoang-Trong et al. (1988); 8 – 9, Sileny (1989); and 10, Hinzen (1982).

Other significant European cases of mine seismicity include (Figure 4): (1) the potash mines in the seismically-active South German Block in Germany; (2) coal mines in the Ruhr district, West Germany; (3) coal mines in the Provence field and the Lorraine Basin in France; (4) iron ore mines near Grängesberg in central Sweden; (5) coal mines in North Staffordshire, United Kingdom; and (6) coal mines in the Kladno district near Prague and in the Ostrava Karvina district in northern Morovia (and the Upper Silesian Basin), both in Czechoslovakia. All cases occur within the compressional regimes of either western Europe, which is characterized rather uniformly by a northwest-southeast maximum principal stress (Müller et al. 1992) or eastern Europe (Figure 4).

In the South German Block, a focal mechanism of a damaging rockburst exhibits reverse faulting and a northwest-southeast P-axis (Knoll and Kuhnt 1990) consistent with the orientation of the regional maximum principal stress (Figure 4). A composite focal mechanism of 21 small tremors ($M_L \leq 2.3$) in the Ruhr district also reveals reverse faulting but in response to a northeast-southwest maximum principal stress (Hinzen 1982) (Figure 4). Reverse faulting focal mechanisms are typically observed for rockbursts in the Provence coal mines (Revalor et al. 1990), which may also reflect an influence of the tectonic stress field. In situ stress measurements in the Provence coal field indicate that the maximum principal stress is about 1.5 times greater than the lithostatic stress (Gaviglio et al. 1990). Most of the mine tremors observed in the Lorraine coal mines are also the result of reverse faulting (Hoang-Trong et al. 1988). Their focal mechanisms exhibit northeast-southwest trending P-axes, almost orthogonal to the northeast-southwest compressive stress direction for western Europe (Figure 4). Unfortunately, no focal mechanisms are available for the Grängesburg rockbursts (Båth 1984) and the mechanisms for the North Staffordshire mines (Westbrook et al. 1980) are not well constrained.

Extensive seismological studies have been performed in the Czechoslovakian coal mines in the past decade. An analysis by Sileny (1989) indicates that Kladno tremors are the result of predominantly normal faulting with varying components of strike-slip faulting and for the Ostrava Karvina events, strike-slip and normal faulting. The Kladno mine seismicity does not apparently reflect a dominant tectonic influence since the normal faulting indicates an extensional stress field rather than the compressive tectonic regime of eastern Europe. The relatively shallow depths of these events (less than 1 km) may account for the lack of a significant tectonic stress influence. Although the Ostrava Karvina strike-slip focal mechanisms show considerable variability, they all exhibit a horizontal maximum principal stress which may reflect some tectonic influence on the mine tremors (Figure 4).

3.4 *South Africa*

The first studies of mine seismicity and certainly the most significant in terms of advancing our understanding of the source processes of mine tremors were performed in the deep gold mines of South Africa. Seismic events thought to be associated with the deep gold mining were first observed in 1908 in the Witwatersrand district.

In one of the earliest seismological studies, Spottiswoode et al. (1971) observed that most large seismic events in the Witwatersrand were the result of shear failure. They determined focal mechanisms for 11 events (M_L 1 to 3.5) in the East Rand Proprietary Mines and found them to be consistent with a source mechanism appropriate for tectonic earthquakes associated with normal faulting. This type of mechanism is compatible with underground observations of burst fractures and with the violent failure predicted by McGarr (1971) on the basis of theoretical stress calculations around a stope. According to McGarr's model, the maximum principal stress is oriented nearly vertical in the hanging wall and footwall in the region of highly stressed rock extending typically 10 m ahead of the face. The focal mechanisms, as expected for normal faulting, all exhibited a vertical maximum principal stress; however, the direction of the minimum principal stress varied considerably, suggesting that a uniform stress field of tectonic origin was not present (Spottiswoode et al. 1971).

From 1971, when a seismic network was established covering the four major mines in the Klerksdorp district, more than 6,000 events ranging from M_L 0.2 to 5.4 were recorded through 1981 (Gay et al. 1984). The mine tremors, including the largest events, appeared to concentrate near faults, especially those with significant lithologic contrasts across them. In situ stress measurements in some areas showed high deviatoric stresses, suggesting that residual stresses (originating from past tectonic deformation) may play a dominant role in the generation of some events (Gay et al. 1984).

Potgeiter and Roering (1984) determined focal mechanisms for 10 tremors, M_L 1.8 to 3.8, that occurred during 1980 and 1981 in the Klerksdorp district. Focal mechanisms of five events located near a major fault and within 25 m of an advancing stope exhibited normal faulting with the maximum principal stress oriented vertically, similar to the observations of Spottiswoode et al. (1971) in the Witwatersrand district. All mechanisms exhibited a nodal plane parallel to the fault, strongly suggesting that the fault had been reactivated by the mining. The remaining events occurred near an intrusive diabase dyke and an advancing stope. Somewhat surprisingly, their focal mechanisms exhibited reverse faulting with the maximum principal stress oriented horizontally and to the northwest. One nodal plane of each mechanism was parallel to the dyke, suggesting shear failure along this structure. According to Potgieter and Roering (1984), the contrast in faulting and associated stress fields of the 10 closely-spaced events suggests that (1) localized residual stresses were principally responsible for the generation of the reverse faulting tremors along pre-existing geologic structures and (2) the normal faulting events were due solely to mining-induced stresses acting on the major fault.

Brummer and Rorke (1990) analyzed five large South African rockbursts, M 3.6 to 5.2, which occurred from 1982 to 1988. All events were the result of slip on pre-existing faults and four of the five tremors, for which the actual fault displacements could be observed, displayed normal slip. In addition, two of the events exhibited both normal and reverse slip. According to Brummer and Rorke (1990), reverse slip is possible when two stopes are involved (see their Figure 10). Such movement will occur in the hanging wall of the upper stope and the footwall of the lower stope. Unfortunately, focal mechanisms are apparently not available for these events; thus the coseismic rupture process involving both normal and reverse slip cannot be characterized.

Based on rather sparse stress data for South Africa compiled and quality ranked as part of the World Stress Map Project, the region appears to be characterized by a strike-slip faulting stress field (vertical intermediate principal stress) at its southern end and an extensional regime (intermediate principal stress generally trending north to northwest) in the rest of the country (Zoback 1992). If indeed the mining districts are located in an extensional regime, this would be unlike other major occurrences of mine seismicity which are located in compressional tectonic regimes.

3.5 *Other Countries*

One of the most significant occurrences of mine seismicity and rockbursts in terms of human and economic losses is in the Kolar gold fields of southern India. Mining has been conducted for more than a century reaching to depths of 3.2 km (Srinivasan and Shringarputale 1990). Although no focal mechanisms for mine tremors have been determined to date, Srinivasan and Shringarputale (1990) classify the mine tremors into: (1) events in close proximity to the active stopes resulting from stress redistribution around the mines and (2) events located away from the stopes due to the redistribution of regional stresses. According to Gowd et al. (1992), the Kolar gold fields are located in a seismically active portion of India which is characterized by northwest-southeast compressive tectonic stresses.

Other important cases of mine seismicity have occurred in: (1) Japanese coal mines including the Horonai mine in the Ikushunbetsu Basin (Sato et al. 1989); (2) southwestern Australia e.g., the Mt. Charlotte gold mine (Lee et al. 1990); (3) metalliferous and coal mines in China such as the Chengzi coal mining district (Mei and Lu 1987); and (4) mines in coal and metallic ores in the Soviet Union including the Tkibuli-Shaorsk coal field (Petukhov 1987). For the Horonai mine, well-constrained focal mechanism data are not available although the solutions that have been determined suggest normal faulting. To my knowledge, no focal mechanisms have been calculated for the Mt. Charlotte, Chinese or Soviet Union mines. Japan and China are characterized by strike-slip faulting stress regimes (northeast to southeast maximum principal stress) and southwestern Australia by east-west compressive tectonic stresses (Zoback 1992). Unfortunately the state of stress is poorly known in the Soviet Union (Zoback 1992) although it is likely that most of the country is subjected to compressional tectonic stresses.

4 DISCUSSION AND CONCLUSIONS

In several occurrences, such as the Sudbury Basin, the eastern Wasatch Plateau, the Coeur d'Alene, the South German Block, and some of the Polish mines, mine tremors, especially the larger events, are indistinguishable from natural tectonic earthquakes which also occur in these regions. Both are the result of reverse and to a lesser extent, strike-slip faulting in response to compressive stresses characteristic of the tectonic stress fields. In some cases, such as the Lorraine Basin, the Ruhr district, the Strathcona mine in the Sudbury Basin, and possibly the Ostrava Karvina district, the P-axes of the focal mechanisms deviate from the regional compressive stress direction suggesting that the tectonic stresses are a significant but not necessarily dominant factor in the generation of the mine tremors. This assumes of course, the uniformity of regional stress fields which is not always the case. In particular, variations of the regional stress field occur in Europe due to localized tectonic sources (Grünthal and Stromeyer 1992). Thus some of the above cases may not actually deviate significantly from the local stress fields. The uncertainties in the P-axes of focal mechanisms, the maximum principal stress direction, and the correlation between them also needs to be considered in such assessments.

Although focal mechanism data are not available for the mine tremors occurring in the Grängesburg, Kolar, eastern U.S., Mt. Charlotte, and Chenghzi mines, they are located in regions characterized by compressive tectonic stresses. Thus based on a review of available focal mechanism data and our current understanding of the state of stress worldwide, it appears that for the most part, the significant occurrences of mine seismicity are located in compressive tectonic stress regimes. Such areas are also often characterized by moderate and sometimes high levels of earthquake activity attesting to active tectonism and significant tectonic stresses.

The observation that cases of mine seismicity generally occur in compressive regimes may not be all that surprising given the fact that much of the earth's crust is being subjected to compressive rather than extensional tectonic stresses. However, mining has been and is being performed, for example, in many areas of the extensional western U.S. with no significant cases of mine seismicity having occurred.

The mine seismicity and rockbursts taking place in the deep gold mines of South Africa may be the major exception. Historically, South Africa has been characterized by only minor earthquake activity and thus tectonic stresses do not appear to be significant as is often the case in such intraplate settings. Yet because of the predominance of normal faulting in South African mine seismicity, extensional tectonic stresses should not be discounted as a factor in influencing the generation of mine tremors and rockbursts in these deeps mines. Given this possibility, the great depth of mining and hence high lithostatic stresses may be the most important factor in the generation of seismicity in these mines although as noted by several investigators, residual tectonic stresses in some cases may also be significant.

It is commonly believed that normal faulting due to stope closure (McGarr 1971) is the mechanism which generates most mine tremors. Examples may be the mine seismicity in the Kladno, North Staffordshire and some of the Polish mines. Thus it is somewhat surprising that reverse and to some extent, strike-slip faulting appears to be the primary mode of deformation in most regions of mine seismicity based on the available focal mechanism data.

These observations suggest that compressive tectonic stresses play a greater role in the generation of mine seismicity worldwide than was previously thought. As has been noted by a number of early researchers (e.g., Smith et al. 1974), the effect of mining in the earth's crust, in a relatively global sense, is to decrease lithostatic stresses through unloading by the removal of mass. The horizontal stresses will also be slightly increased or decreased due to the unloading and Poisson's effect (Wong 1985). In a compressive stress regime, this effect will advance pre-existing zones of weakness such as faults toward failure by decreasing the vertically oriented minimum principal stress and increasing any shear stresses acting on the faults (Figure 1). (Note in a strike-slip stress regime, unloading mainly decreases the intermediate principal stress although the horizontal maximum or minimum principal stresses will also be altered possibly resulting in increased shear stresses along steeply dipping faults.) As a result, coseismic rupture may occur depending on the coefficients of friction along such faults and their orientation with respect to the maximum principal stress. This effect is illustrated by the familiar Mohr circle diagram (see Figure 6 in Wong [1985]). In mines where extraction is being conducted at multiple levels, the unloading effect can occur throughout the workings.

In addition to this unloading effect, mining obviously leads to stress redistribution around the mine openings where both the in situ vertical and horizontal stresses can be altered. Again in a compressive stress regime, a decrease in the lithostatic stress (minimum principal stress) or increase in the maximum horizontal stress can lead to failure and mine seismicity.

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